An ~~Alpine Drought Impact I~~inventory of Alpine drought impact reports to explore past droughts in a mountain region

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Abstract. Drought affects even mountain regions, despite a humid climate. Droughts' damaging character in the past and an increasing probability in future projections call for an understanding of drought impacts in the European Alpine region. The European Drought Impact ~~Report~~ report Inventory (EDII) collects text reports on negative drought impacts. This study presents a considerably updated EDII focusing on the Alpine~~study~~ region ~~of the greater 'Alpine Space'~~. This first version release of an Alpine Drought Impact report Inventory ($EDII_{ALPS}$) classifies impact reports into categories covering various affected sectors and enables comparisons of the drought impact characteristics. We analyzed the distribution of reported impacts on the spatial, temporal and seasonal scale, and by drought type for soil-moisture and hydrological drought. For the spatial analysis, we compared the impact data located in the Alpine region~~Space'~~ to the whole of Europe~~entire Europe~~. Further, we compared impact data between different climatic and altitudinal domains (Northern vs. Southern region, pre-Alpine vs. high-altitude region), and between the Alpine countries. Compared to the whole of Europe~~entire Europe~~, in the Alpine region~~Space~~ agriculture and livestock farming impacts are even more frequently reported, especially in the Southern region. Public water supply is the second most relevant sector, but overall less prominent compared to Europe, especially in spring when snowmelt mitigates water shortages. Impacts occur~~red~~ mostly in summer and early autumn with a delay between those impacts initiated by soil-moisture drought and those initiated by hydrological drought. The high-altitude region shows~~ed~~ this delay~~effect~~ the strongest. From 1975 to 2020, the number of archived reports ~~increased~~increases, with substantially more impacts noted during the drought events of 1976, 2003, 2015 and 2018. Moreover, reported impacts ~~diversified~~ diversify from agricultural dominance to multi-facetted impact types covering forestry, water quality, industry and so forth. Though $EDII_{ALPS}$ is biased by reporting behaviour, the region-specific results ~~amount of more than 3200 compiled reports~~ of~~n~~ negative drought impacts across the water-rich European mountain region demonstrates the need to move from emergency response~~actions~~ to ~~better~~ prevention and preparedness actions. These may be guided by $EDII_{ALPS}$' insights to regional patterns, seasons and drought types.

1 Introduction

Droughts are natural hazards, which can cause widespread and severe impacts on the environment and societies. Compared to other weather-related hazards, such as floods and storms, droughts are among the most damaging events in terms of affected people and economic costs (Wilhite, 2000a; UNISDR, 2009; UNDRR, 2019). The summer droughts of 2003, 2015 and 2018 have raised concerns about the vulnerability of the European water budget to climate change (Weingartner et al., 2007; Teuling, 2018), because these events have affected more than 17 % of the European population (Mastrotheodoros et al., 2020). Due toBecause of the humid mountain climate, with an annual total precipitation between 400 to beyond 3000 mm/year (Isotta et al., 2014) and the four major European rivers Po, Rhone, Rhine, and Danube, the Alps are also called the "Water towers for Europe" (Viviroli et al., 2007). Nonetheless, past droughts caused severe impacts such as limited supply of water for drinking, irrigation and hydropower generation (Haslinger et al., 2019). The predicted increase of drought frequency, duration and extent stresses the relevance of systematic analysis of drought impacts and their cascading effects in mountainous areas. This is particularly relevant within the Mediterranean climate in the Southern parts of the Alpine regions, where recent drought events triggered water disputes and spread of multiple impacts (Yves et al., 2020). The need to understand the role of drought impacts in Europe's mountainous region is stressed by the fact that more than 170 million people live within the major river basins (Viviroli et al., 2007). Until now and to the best of our knowledge, only the expert paper by the "Water management in the Alps" platform (Water Management in the Alps Platform of the Alpine Convention, 2018) is a transnational study focusing on drought impacts in the Alpine region presenting experiences, approaches and common challenges for water management by stakeholders. This expert paper emphasizes the need to move from emergency to preparedness actions, essential for the Alpine-wide research on past drought and potential future impacts.

Drought builds up slowly and accumulates over time with cascading effects and the provoked impacts may linger for years after termination (Wilhite, 2000b). Compared to other disasters these characteristics brought up different drought definitions with the difficulties to determine the onset and termination of the phenomenon. A common approach is to define drought as a sustained period of below-normal water availability (Tallaksen and van Lanen, 2004) and classify the phenomenon into different four types that generally occur in the following order (Wilhite and Glantz, 1985; van Loon et al., 2016): (1) Climate variability leads to precipitation deficit causing meteorological drought (D_M), the initiator for the other types. Meteorological drought combined with high potential evapotranspiration leads to (2) agricultural or soil--moisture drought (D_{SM}). (3) Hydrological droughts (D_H) occur delayed, associated with the effects of temperature anomalies, precipitation shortfalls, and/or anthropogenic demand pressures on surface or subsurface water supply (e.g. streams, reservoirs, lakes or groundwater). (4) Socioeconomic drought (D_{SE}) is associated with an inadequate supply of some economic goods resulting from meteorological, agricultural, and hydrological droughts. In a mountain-to-foothill region this propagation may differ as hydrological processes vary from high to low elevations. The annual hydrological cycle may be more likely to be reset every year by winter snow,. In addition, response and reaction times are fast, gradients steep and storages more local and diverse.

The different drought types generally lead to a wide range of impacts, making an impact assessment more difficult compared to other disasters. D_M is typically understood as the prime trigger. While and D_M impacts in lowlands may often have compound causes with heat waves in lowlands, e.g. excess mortality as a result of cardiovascular diseases.~~,~~ ~~in~~ In~~cooler~~ mountain regions such direct -impacts are likely less relevant due to the cooler climate. Most of these direct drought impacts can be linked to either D_{SM} or D_{H}. For example, low soil moisture typical for D_{SM} initiates reduced vegetation health or crop quality, whereas low discharge and/or groundwater storage typical for D_{H} causes problems in Public water supply (Wilhite and Vanyarkho, 2000). Drought ~~I~~impacts not directly induced by the conditions of D_{SM} or D_{H}, are also called~~known~~ as "2nd-level" or "indirect" impacts.~~-~~(Wilhite and Vanyarkho, 2000). Typical examples for such impacts are ~~, such as~~ increased costs due to supplementary irrigation, increased disease attacks on trees or water allocation conflicts. For these impacts drought can be the trigger~~initiator~~, but none of the described types can be identified as the exclusive driver. Therefore, they are known to be the least tangible.~~.~~

~~In mountain regions economic sectors and priorities or activities may differ. These indirect impacts are the least tangible and often related to D_{SE}.~~ In order to link drought impacts specifically to drought types, D_{SM} and D_{H} are the most evident types (Stagge et al., 2015). Despite the challenge to identify drought impacts, several efforts have been made predominantly focusing on the agricultural sector (Logar and van den Bergh, 2013; Poljanšek et al., 2019; Cammalleri et al., 2020), but not specifically on mountain regions or mountain-to-foothill transitions. Stahl et al. (2012) introduced the European Drought Impact r~~R~~eport Inventory (EDII) to widen the perspective to the broad scope of drought impacts including more sectors, such as *Public water supply*, *Tourism and recreation* and *Energy and industry*. The EDII defines drought impacts as negative consequences for environment, society or economy and classifies these into 15 sectoral categories with multiple subtypes. Blauhut et al. (2016) and Stahl et al. (2016) used these geo-referenced reports to compare sectoral differences across Europe, which demonstrates the value of this impact inventory. Stagge et al. (2015) and Bachmair et al. (2016) statistically modelled the likelihood of~~went even further and predicted~~ impacts based on ~~the~~ EDII data.

This study builds up on the drought impact data collected and classified in the EDII, expanding it with the help of existing databases to develop a~~n~~ mountain specific "Alpine Drought Impact report Inventory ($EDII_{ALPS}$)" ~~Alpine-specific drought impact inventory~~. The main objective is to survey, classify and systematically assess past drought impacts in the European Alpine region with the following leading questions:

- How do impacts differ in such a mountain-foreland region compared to the whole of Europe? Are there any spatial patterns within the Alpine region~~Space~~ driven by altitudinal or climatic conditions (high-altitude region, pre-Alpine region, Northern and Southern region)?
- Are there any trends of drought impact frequencies over time, overall and for different ~~time ranges (e.g.~~ seasons~~)~~?
- ~~How are the drought types impacts distributed in the Alpine Space? Can we link the impacts' location to drought types of D_{SM} and D_{H}?~~ Are there seasonal differences in the occurrence of impacts related to soil moisture versus impacts related to hydrological drought?

2 Methods

2.1 The study region and its specific characteristics

Our study region is the so-called “Alpine Space” introduced by the EU-funded programme of the same name (Fig. 1, Interreg-Alpine Space Programme 2014-2020). The Alpine Space covers the Alps and their foothills, as well as different climatic zones and therefore allows the consideration of water and resource flow and exchange typical to mountain regions. With the study region’s extent, we therefore include drought impacts not only at high altitudes, but also in downstream areas of the water-rich source regions (e.g. the river basins Po, Rhine, Danube etc.). We updated the content and analyzsed impact patterns within subregions of the Alpine Space and compared this newe whole of the $EDII_{ALPS}$ Alpine Space with the pan-European region with the help of EDII with the whole pan-European region of the EDII (Stahl et al., 2016) whichthat we name $EDII_{EU}$ in all comparisons (Fig. 1).

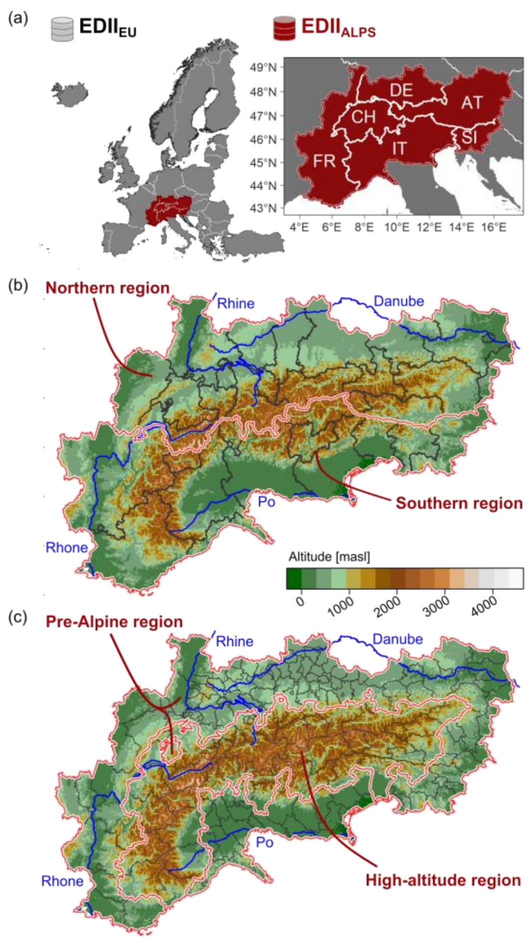

Figure 1. (a) The $EDII_{EU}$ coverageing of the whole of Europe as described in Stahl et al., 2016 and. The $EDII_{EU}$ integratinges the area covered by the new updated Alpine Drought Impact report Inventory ($EDII_{ALPS}$). EDIIALPS coversing the “Alpine Space" study area across the different Alpine countries for which we updated the original EDII. The $EDII_{ALPS}$ in its paired domains for the analysis are: (b) the Northern and Southern region divided by grouped NUTS 2 regions, and (c) the pre-Alpine and high-altitude region divided by grouped NUTS 3 regions. The “Alpine Space” study area within Europe (a) for which the Alpine Drought Impact

~~Inventory (EDII$_{ALPS}$) was developed, showing the major rivers draining the Alps and the paired subregions for the analysis: (b)on the left the Northern and Southern region divided by grouped NUTS 2 regions, and (c)on the right the pre-Alpine and high-altitude region divided by grouped NUTS 3 regions~~.

The Alpine Space boundary corresponds to the borders of NUTS regions. The Nomenclature of Units for Territorial Statistics (NUTS) is a spatial unit with levels 1, 2 and 3 used in the European Union to subdivide countries into major, middle in minor regions for statistical purposes (Eurostat, 2020). Using these NUTS regions, we split ~~grouped~~ the Alpine Space into two subdivisions ~~four domains~~ in order to compare contrasting climatic and altitudinal conditions: (1) The "Northern region", with all NUTS 2 (and thus including all NUTS 3) regions characteri~~z~~sed by maritime climate versus (2) the "Southern region" with the other NUTS regions characterized by the Mediterranean in the South and Southwest and continental climate in the Southeast (Bouma, 2005). Haslinger et al. (2019) presented a strong North-South dipole along the Main Alpine Crest for dry and wet areas during the last 210 years. (3) The "high-altitude region" identified with NUTS 3 regions for which ≥ 30 % of the area are higher than 1000 masl versus (4) the "pre-Alpine region" covering all remaining NUTS 3 regions. For the altitudinal comparison, we chose ~~the spatially higher resolved~~ NUTS 3 regions with a higher spatial resolution, because altitudinal characteristics do present stronger the smaller the area. In the following the term "domains" includes the pre-Alpine, high-altitude, Southen and Northern region,~~se four subregions~~, the Alpine Space covered by the EDII$_{ALPS}$ and Europe covered by the EDII$_{EU}$, and thus differs from smaller spatial units.

2.2 Collection and pre-processing of drought impacts~~'~~ data

We retrieved drought impact data from different sources located in the European Alpine countries considerably updating the latest version of the ~~European Drought Impact Report Inventory~~ EDII (i.e. status of EDII from September 2019, Stahl et al., 2016, https://doi.org/10.5194/nhess-16-801-2016). The EDII itself archives text-based reports on drought impacts from different sources, most frequently from newspaper articles, web pages, scientific or governmental reports, databases and other information sources. The first archived impact report dates~~goe~~s back to 1448. This ~~very~~ historical information for southwestern Germany was retrieved from the collaborative research environment tambora.org (Glaser et al., 2015, https://www.tambora.org/). However, most collected reports stem from the late 20th C~~c~~entury till now. For the search of text-reports we applied the same method described in Stahl et al. (2016) and focus~~ed~~ing on the last 20 years. The compiled~~the We compiled~~ impact data had to fulfill ~~by applying the same search method described in Stahl et al. (2016) and fulfilling~~ the standards the EDII requires in order to be consistent, e.g. impact description, reference, location and timing. Therefore, our impact collection is a substantial update for EDII with a region-~~-~~specific focus. ~~Our~~ Subsequently, the collected impact ~~data~~ reports ~~came~~ come from sources located in the different Alpine~~-~~ countries: (1) A broad variety of Italian and (2) German text-reports, (3) the French platform Propluvia (Ministère de la Transition Écologique et Solidaire, http://propluvia.developpement-durable.gouv.fr), (4) the Austrian chronicle of severe weather impacts "Unwetterchronik" (Zentralanstalt für Meteorologie und Geodynamik, https://www.zamg.ac.at/cms/de/klima/klima-aktuell/unwetterchronik), (5) the Drought Management Center for Southeastern Europe (DMCSEE, http://www.dmcsee.org/) covering Slovenia

~~(Slovenian Environment Agency)~~ and Slovenian text-reports, and (6) the media archive of the Swiss information platform Drought-CH (Zappa et al., 2014, https://www.drought.ch/). Most of the reported impacts of the German, Italian and Slovenian text-reports stem from newspaper articles, whereas the platforms Propluvia, Unwetterchronik, DMCSEE, Drought-CH are data archives that we (re-)investigated to extract and translate drought impact information to EDII fulfilling the described requirements.

Complying with the EDII guidelines (www.geo.uio.no/edc/droughtdb/img/Guidelines_EDII_Webversion.pdf), these sources offered drought impact information as negative consequences of drought as text-based reports (Italian and German reports, Unwetterchronik, DMCSEE, Drought-CH). A typical recorded entry in relation to *Agriculture and livestock farming* is described in the following example: "In some regions in lower Austria the grain harvest was less than 50 %, especially for wheat and canola. [...] The first cut of grasslands summed up to only two thirds of the normal yield [...]. Higher costs for irrigation appeared. The federal state of lower Austria supported the farmers with 1.5 million euros for the so-called 'Feeding stuff ac~~-~~quisition' [...]." This report was published in August, 2003, by the Austrian centre for agricultural information. Anotehr~~n read exemplary~~ summarized description related to a drought impact on management of livestock on higher-elevated pasture that was published in October, 2018 by the Unwetterchronik reads: "Due to persisting drought some meadows in the district of Landeck could not be cut a second time [...]. There were losses between 60 to 100 %. [...] Due to fodder shortage the farmers had to buy additional hay or sell their animals. [...] In Oberland the ~~alpine~~ Alpine pasture farmers brought their cattle down to the valley earlier, as there was a lack of fodder and drinking water." A typical example related to water supply is the following report published in July, 2015 by a regional Italian newspaper: "In Trento fountains were closed. At the Arco municipality drought conditions are severe with water use bans. The civil protection monitors the level of the Lago delle Piazze, where different sectoral water demands can quickly worsen the current conditions." In contrast to the other sources, Propluvia ~~offered~~ offers mapped management strate~~-~~gies across France, classified by increasing warning levels dependent on the drought severity. For example, the warning level 'reinforced alert' means that in the mapped region bans on watering gardens/lawns, open spaces, golf courses, and washing the car ~~at certain times~~ are taking place at certain times. Further, the reduction of withdrawals for agricultural purposes less than or equal to 50 % and measures prohibiting valve operations and nautical activity are applied. This way, Propluvia provides information about negative drought impacts with specific measures for the society and economy that could be translated into the EDII database entries.

For our study region ~~W~~we compiled data within the Alpine Space and with available information for at least NUTS 2 regions and at least with the information on a given season or month of a year in which an impact started to occur. We then classified the impact data into 13 (out of 15) categories and to 96 subtypes related to the potentially most impacted sectors proposed by the EDII: *Agriculture and livestock farming* (1), *Forestry* (2), *Freshwater aquaculture and fisheries* (3), *Energy and industry* (4), *Waterborne transportation* (5), *Tourism~~Tourims~~ and recreation* (6), *Public water supply* (7), *Water quality* (8), *Freshwater ecosystems* (9), *Terrestrial ecosystems* (10), *Air quality* (13), *Human health and public safety* (14), and *Conflicts* (15). We excluded the EDIIs categories *Soil system* (11) and *Wildfires* (12) as the link between drought, impact and management in these categories is often inconclusive and other databases, such as the Forest Fire Information system (EFFIS, 2020) are more comprehensive. The final categori~~z~~sation enabled the analysis of spatial distribution, temporal trends and differences by drought and impact type. The resulting dataset of this systematic collection and classification of impact data with specific focus on ~~within~~ the Alpine Space is a sub database of the EDII. Due to the regional focus and some described adaptations we call this dataset in its first version ~~is~~: $EDII_{ALPS}$ V1.0 available from the FreiDok repository (doi: tbd, last update 8th of January, 2021).

The distributions of all reported~~s~~ impact categories from the $EDII_{ALPS}$ were compared with those of the $EDII_{EU}$ ~~entire Europe~~ including the Alpine Space ~~($EDII_{EU}$)~~ (Fig. 1). Within $EDII_{ALPS}$, we compared the pre-Alpine and high-~~Alpine~~altitude region, the Northern and Southern Alpine region~~s~~, as well as ~~political units:~~the countries (respectively the part of the country within the Alpine Space), and the NUTS 2 ~~and 3~~ regions (Fig. 1). Because the total counts of reports ~~numbers~~ differ among these areas, we additionally focused on relative proportions (‘fractions’) of the 13 categories, i.e. information that is independent of the overall data availability.

For the investigation of temporal trends, we aggregated $EDII_{ALPS}$ data per year. In addition, we aim to identify potential drought events from the impact perspective by comparing these aggregated yearly impacts. ~~and compared the proportions of the most frequent impact categories for the drought events 1976, 2003, 2015 and 2018~~. For the seasonal analysis, we pre-processed impact data as follows.~~:~~ Within the data collection, each impact was assigned to a month or season, in which the impact started to occur. Most of the time, information about the end of an impact was unavailable. In this case we assumed that the impact only occurred in that month or season and not beyond. When a starting season is given for an impact, we assigned the season "spring" to the months March, April, May (MAM), "summer" to June, July, August (JJA), "autumn" to September, October, November (SON), and "winter" to December, January, February (DJF) for monthly impact data.

Different drought types may lead to different impacts, with D_{SM} typically related to impacts in agriculture and D_H typically related to impacts within a range of several water uses, such as the ~~*Public*~~ water supply. In this study, we focu~~s~~sed on the D_{SM} and D_H type,~~.~~ as D_M often does not lead to impacts directly. ~~and D_{SE} is challenging to relate to specific impacts, as they are the least tangible. Additionally~~Further, impacts on agriculture and on various water uses are among the most relevant concerning drought (Stahl et al., 2016). To analyse timing, amount and the relevance of specific impacts, we re-grouped impact data to the D_{SM} or D_H type using the subtype category for assignment. For instance, within the category *Energy and industry* (4) subtypes are e.g. ‘Reduced hydropower production’ (4.1) and ‘Impaired production’ [...] (4.2) (Stahl et al., 2016). Regardless of the corresponding primary category, these subtypes were assigned to D_{SM} and/or D_H. For example, ‘Reduced hydropower production’ (4.1) is a result of low discharge and is therefore assigned to D_H, whereas ‘reduced productivity of annual crop cultivation’ (1.1) is a result of low soil moisture and therefore assigned to D_{SM}. Based on expert knowledge, four different people ~~identified~~ independently identified for all 96 subtypes either the assignment to D_{SM} and/or to D_H ~~.~~(final~~all~~ assignment rules~~s~~ are presented in Table S1). The newly grouped D_{SM} and D_H impacts were then analysed for seasonal occurrence in the different domains ($EDII_{EU}$~~entire Europe~~, $EDII_{ALPS}$ ~~Alpine Space~~, pre-Alpine and high-altitude region, Southern and Northern region). We calculated smoothed seasonal “impact regimes” as loess curves, i.e. by local regression (Cleveland, 1979).

2.3 Hypothesis testing

The following hypotheses on spatial differences were tested: the distribution of impact categories of~~reported by~~ the EDII$_{ALPS}$ ~~for the Alpine Space~~ differed from that of~~by~~ the EDII$_{EU}$~~of the entire European region~~, the distribution of the high-altitude region from that of the pre-Alpine region, the distribution of the Northern region from that of the Southern region. Additionally, we tested the hypothesis that the distribution of reported impact categories of EDII$_{ALPS}$ differed between the Alpine countries and the NUTS 2 regions. We tested as well, if the distribution of impact categories differed for the years between 1975 and 2020. At last, we tested whether the distribution of reported impact categories ~~reported~~ differed for the seasons spring, summer, autumn and winter in the ~~regions~~domains (EDII$_{EU}$ ~~Europe~~, ~~the~~ EDII$_{ALPS}$ ~~Alpine Space, the~~, pre-Alpine, high-altitude, Northern and Southern regions).

For the statistical analyses, we used the compiled impact data as count data. We applied the *Pairwise Wilcoxon Rank Sum Test* to test whether the fraction of the counted data were significantly different. The test analysed if the central tendencies of the distributions between the groups differed, such as between the paired domains, the countries, the NUTS 2 regions and the seasons ~~groups~~ (Cuzick, 1985). With the p-value ≤ 0.05, we rejected the null hypothesis that tendencies among the tested groups had been ~~are~~ the same and concluded a statistically significant difference between them. In addition, if we tested more than two groups, this test allowed us to identify which group(s) was (were) significantly different, ~~if we tested more than two groups~~, e.g when we tested all 35 NUTS 2 regions.

3 Results

3.1 Spatial differences across domains and countries

With our update ~~A~~a~~s~~t the time of this study EDII$_{EU}$ for~~covering~~ the whole of Europe contains~~mpris~~ed in total ~~around~~ more than 10,~~6~~100 reported drought impacts for NUTS 2 and 3 regions. ~~The first version of EDII$_{ALPS}$ summed up to more than 3,200 impacts~~. For~~Regarding~~ the Alpine Space, our newly compiled impact data has raised substantially the number of archived reports from 1412 (i.e. status of EDII from September 2019) to more than 3,000 (EDII$_{ALPS}$ V1.0, last update 8th of January, 2021). For the EDII$_{ALPS}$ we could add missing drought impact reports especially located in Austria, Slovenia, Italy and France.~~ (F~~for detailed information on the numbers and distribution of~~effect of~~ our update refer to the Supplementary material, Sect. 2). We observed substantial differences between the amounts of reported impacts across the domain of the Alpine Space (Fig. 2) with ~~most~~ more reports located in the Northern than in the Southern region and more in the pre-Alpine than in the high-altitude region~~, followed by the Southern and high-altitude region~~. The *Pairwise Wilcoxon Rank Sum Test* depicted significant differences between the impact category distributions of the EDII$_{ALPS}$~~Alpine Space~~ and the EDII$_{EU}$~~Europe~~, but not between the other pairs (Table 1). Among the Alpine countries, the test identified Slovenia to be significantly different from Austria and Germany. At the smaller scale, several NUTS 2 regions located in Italy differed to NUTS 2 regions in Austria, Switzerland and Germany (Table 1, Figure 2a).

In addition to the test results, relative ~~distributions~~ fractions provide further information (Fig. 2). The EDII$_{ALPS}$ and the EDII$_{EU}$ report the same two most frequent impact categories: *Agriculture and livestock farming* (EDII$_{ALPS}$: 48 %, EDII$_{EU}$: 30~~1~~ %) and *Public water supply* (EDII$_{ALPS}$: 19~~21~~ %, EDII$_{EU}$: 2~~5~~4 %). More than half of all reports on drought impacts belong to these two ~~sectors~~ categories in both regions. With 6~~1~~7 % this dominance is even stronger in the EDII$_{ALPS}$ (EDII$_{EU}$: 54~~6~~ %). The fraction of reported impacts in *Agriculture and livestock farming* ~~was~~ is clearly higher in all domains in the EDII$_{ALPS}$~~Alpine Space~~ compared to the fraction ~~average~~ of the EDII$_{EU}$~~Europe~~. Especially, the Southern region ~~presented~~ presents almost 60 % of the reported impacts in this category, with more than half of all reports related to the subtypes ‘Reduced productivity of annual [...]’ (1.1) or ‘[...] permanent crop cultivation’ (1.2) and ‘Agricultural yield losses ≥ 30 % of normal production’ (1.3). This is related to 96 % of all impacts in *Agriculture and livestock farming* on country-level in Slovenia. The subtype ‘Reduced availability of irrigation water’ (1.4) ~~was~~ is the most prominent in the high- altitude region. Impacts related to the second most important category *Public water supply* ~~were~~ are less frequent~~often reported~~ in the EDII$_{ALPS}$~~Alpine Space~~ compared to the EDII$_{EU}$~~average in Europe~~. In the EDII$_{ALPS}$~~Alpine Space~~, the high-altitude region depicts~~ed~~ the highest fraction with 30~~1~~ %.~~,~~ O~~and o~~n country-level, France (Fig. 2a) ~~stood~~ stands out with 36~~9~~ %.~~,~~ B~~b~~oth regions exceeded~~ing~~ the overall fraction of this category in~~of~~ the EDII$_{EU}$~~European average~~. The most common subtype in this category ~~was~~ is ‘Bans on domestic and public water use’ (7.3).

The third most frequent category in the EDII$_{EU}$ ~~was~~ is clearly identified with *Freshwater ecosystems* (11 %). For the EDII$_{ALPS}$’ third rank, we identify~~ied~~ *Forestry* (7 %) with a slightly higher fraction than *Freshwater ecosystems* (6 %). 16~~7~~ % of all entries in the German part of the Alpine countries and 13 % of the Swiss entries related to *Freshwater ecosystems*, and thus, exceed~~ed~~ the fraction of EDII$_{EU}$~~European average~~. Most of these impacts ~~were~~ are located at the Rhine river and most frequent with the subtype ‘Increased mortality of aquatic species’ (9.1). The EDII$_{ALPS}$’ impacts on *Forestry* (7 %) ~~were~~ are as well mostly located in the German (19 %) and Swiss (10 %) part of the Alpine Space (Fig. 2a). In the EDII$_{EU}$ the category *Forestry* is ranked 6th with a fraction of 6~~5~~ %. In both the EDII$_{EU}$ and the EDII$_{ALPS}$, we ~~identified~~ identify the same most relevant subtype ‘Reduced tree growth and vitality’ (2.1).

The EDII$_{ALPS}$ ~~presented~~ presents these four described categories *Agriculture and livestock farming*, *Public water supply*, *Freshwater ecosystems* and *Forestry* among the most important ones for ~~the~~ all domains, but as well on the country-level with the following differences (Fig. 2a,b). As already mentioned, reports located in Slovenia ~~were~~ are clearly dominated by the category *Agriculture and livestock farming* (96 %). More than 70 % of the impacts located in France (70~~7~~ %)~~-~~, Italy (78 %), and Austria (72 %) report~~ed~~ drought affecting *Agriculture and livestock farming* and *Public water supply* with switching relevance. Impacts located in Germany and Switzerland present~~ed~~ less dominance by these two categories, as *Forestry* and *Freshwater ecosystems* play~~ed~~ as well a major role.

Regarding the other categories and subtypes, we observe~~d~~ smaller differences. Impacts related to *Waterborne transportation* ~~presented~~ present the 4th and 5th highest fraction ~~for both, the (~~EDII$_{EU}$: ~~(9~~10 %~~) and~~, EDII$_{ALPS}$: ~~(~~5 %). The impact frequency~~relevance~~ ~~was~~ is lower in the EDII$_{ALPS}$~~Alpine Space~~, but high in the French part with 18~~4~~ % and in the high-altitude region with ~~7~~8 % of all impacts related to this category (Fig. 2a,b). Whereas the EDII$_{EU}$ impacts ~~across entire Europe~~ relate~~d~~ most to the subtype ‘Impaired navigability of streams (reduction of load [...])’ (5.1), the majority of the impacts in the EDII$_{ALPS}$~~Alpine Space~~ ~~were~~ are not tangible to a specific subtype. They relate~~d~~ to ‘Others’ (5.3), with a majority from the French database~~,~~ Propluvia mapping ‘measures prohibiting valve operation, nautical activity’, which we could not ~~be~~ clearly assign~~ed~~ to any subtype of the category *Waterborne transportation*.

In the EDII$_{EU}$ and the EDII$_{ALPS}$, the category *Water quality* present~~ed~~ a fraction of 7 % and 4 %, both with the most frequent subtype '(Temporary) Water quality deterioration / problems of surface waters [...]' (8.2). Thus, the frequency of impacts reported for this category ~~was~~ is lower in the EDII$_{ALPS}$~~Alpine Space~~.~~, and mostly~~ Most of these impacts are located in Italy with 7 % meeting the reporting frequency of ~~fraction~~ ~~by~~ the EDII$_{EU}$~~.~~ (Fig. 2a,b). The categories *Air quality*, *Freshwater aquaculture and fisheries*, *Tourism~~Tourims~~ and recreation*, *Terrestrial ecosystems*, *Energy and industry*, *Human health and public safety* and *Conflicts* ~~did~~ do not depict an obvious relevance in any of the analysed regions.

3.2 Temporal trends and drought years

Before the year 1950 the EDII$_{ALPS}$ only contains a small number of reported impacts (n: 342~~244~~), covering eight categories, dominated by *Agriculture and livestock farming* (n: 270~~2~~) and followed by *Public water supply* (n: 23), *Energy and industry* (n: 16), *Forestry* (n: 13) and *Human health and public safety* (n: 11). In this early time-period most impacts ~~were~~ are reported in ~~Austria,~~ Switzerland, Germany, Austria and France. The number of reported impacts increases~~d~~ substantially after 1975, and again after 2000 and 2010 (Fig. 3a,b). 2019 and 2020~~Only the last three years~~ had~~presented~~ less impact reports. After 1975, the years 1976 (n: 120), 2003 (n: 401), 2015 (n: 452~~63~~), and 2018 (n: 365~~412~~) show~~ed~~ substantially more impacts than all other years. The *Pairwise Wilcoxon Rank Sum Test* confirms~~ed~~ the years 2003, 2015 and 2018 to be significantly different from others. Thus, our impact data represents four specific drought years. Beside the increase of collected impacts over time, the diversification increase~~d~~ as well.

Comparing the identified drought events (Fig. 3c~~b~~), ~~the extreme relative dominance of~~ the category *Agriculture and livestock farming is extremely dominant* in 1976 (82 %) and much less present~~apparent~~~~decreased substantially~~ in the years 2003, 2015 and 2018 (33 %, 28 %, and 27~~9~~ % respectively). In 1976, the second most reported impacts ~~were~~ are ~~for~~ on *Forestry* (12 %), whereas the other categories are not reported or with low relevance. The year 2003 ~~showed~~ shows high fractions for *Public water supply* (24 %) followed by *Freshwater ecosystems* (20 %) and *Water quality* (12 %), but still dominated by *Agriculture and livestock farming* (33 %). The most frequent subtypes during this drought event ~~were~~ are 'Agricultural yield losses ≥ 30 % of normal production [...]' (1.3) and 'Increased mortality of aquatic species' (9.1). The ~~categorial impact distribution~~fractions of 2015 differ~~was comparable~~ to the one of 2003 as follows~~with the following alterations~~. In 2015, we observe~~d~~ more reports related to *Forestry* (8 %) and *Waterborne transportation* (6 %), but less to *Agriculture and livestock farming* (28 %), *Freshwater ecosystems* (13 %), *Water quality* (8 %) and *Energy and industry* (3 %). Further, the categories *Terrestrial ecosystems*, *Human health and public safety* and *Tourism~~Tourims~~ and recreation* ~~were~~ are represented with low relevance. In addition, no subtype ~~presented~~ presents the fraction ≥ 10 % (Fig. 3c). The fractions of ~~general picture of the year~~ 2018 ~~was~~ are comparable~~ as well~~. Impacts related to *Agriculture and livestock farming*, *Public water supply* and *Freshwater ecosystems* ~~did~~ do not change their fractions remarkably between 2003 and 2015. Within these categories, the subtypes 'Reduced availability of irrigation water' (1.4) and 'Bans on domestic and public water use' (7.3) ~~were~~ are more frequent in 2018 compared to 2015 and 2003. Furthermore, the year 2018 show~~ed~~s~~ again~~ higher fractions in *Forestry* (14~~3~~ %), *Waterborne* *transportation* (109 %) and *TourismTourims and recreation* (65 %) and less in *Energy and industry* (3 %) and *Water quality* (1 %).

Table 1. Results of the *Pairwise Wilcoxon Rank Sum Test comparing the central tendencies between different regions: the paired domains and smaller subregions. For the subregions we limited the shown results are shown only for to those combinations differing by with a p-value <= 0.15. We marked significant differences with '*' (p <= 0.05)..*

Regions[1]	P-value[21]
Alpine Space vs. Europe	0.022*
Pre-Alpine region vs. Northern high-altitude region	0.07785
Northern region vs. Southern region	0.097
Alpine countries (n=5)	
Austria:Slovenia	0.010*
Switzerland:Slovenia	0.063
Germany:Slovenia	0.035*
Alpine NUTS 2 regions (n = 35)	
Provincia Autonoma di Bolzano/Bozen:Niederösterreich	0.115
Provincia Autonoma di Bolzano/Bozen:Ostschweiz	0.143
Provincia Autonoma di Trento:Ostschweiz	0.134
Provincia Autonoma di Bolzano/Bozen:Freiburg	0.031*
Provincia Autonoma di Trento:Freiburg	0.050*

[1]Pairs for regions with more than two subregions (n=2) where central tendencies differ with a p-value ≤ 0.15.

[2]marked with '*' for significant p-value ≤ 0.05.

1 '*' significant at p-value ≤ 0.05.

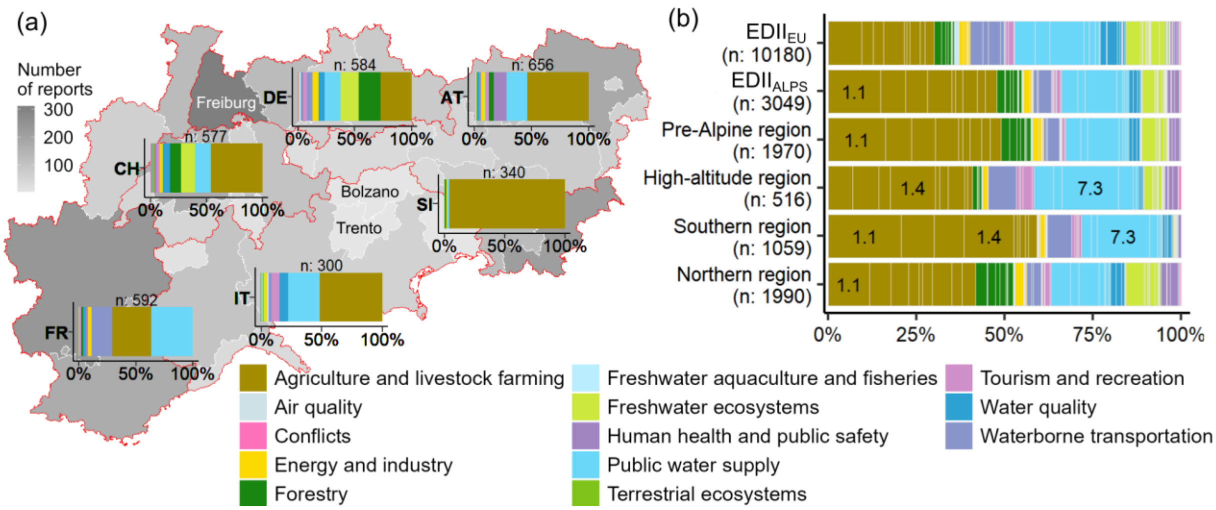

Figure 2. Reported impacts in 13 coloured categories by region (n = total no. of reports per region). (a) FractionProportion of impact category per country. Darker grey shading relates to a higher count of reports per NUTS 2 region. We labelled NUTS 2 regions with significant differences are labeled (see Table 2). (b) Fraction Proportion of impact categories (coloured) covering several subtypes (faint lines) for the domainsregions. Subtypes with a fraction proportion ≥ 10 % per domainregion are labeled.

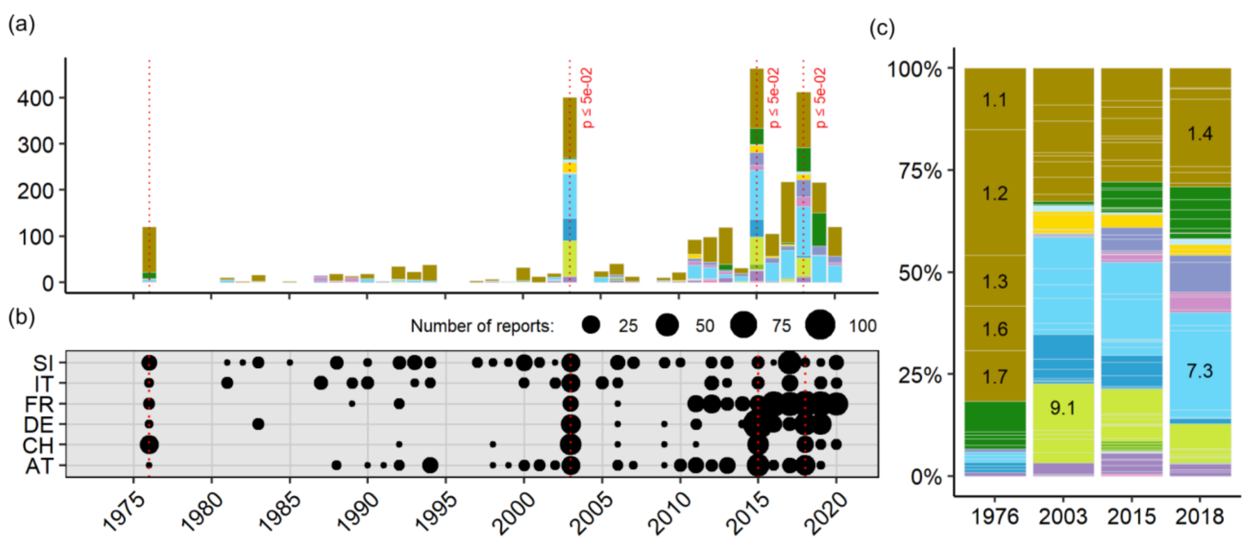

Figure 3. Reported impact categories between 1975 and 2020. (a) NumberCounts of reports per year, and identified drought events (red dotted line) with significantly different years labeled outstanding years marked with red dotted lines and addeded. (b) Number Counts of all reports per country and year. (c) Fraction of impactRelation between sectors categories (coloured) and their subtypes (faint lines) for drought eventsthese years. Subtypes with a fraction proportion ≥ 10 % per region are labeled. Colours see Fig. 2. Colours correspond to the legend of Fig. 2.

3.3 Seasonal patterns

Across all domainsAll -reported drought impacts occurred mostly in summer, followed by either spring (Southern region) or autumn (all other domains), spring and fewest in winter (Fig. 4). Significant seasonal differences were are found in the EDII$_{EU}$ Europe and in the pre-Alpine and high-altitude region of the EDII$_{ALPS}$in the Alpine Space (Table 2),with the summer always significantly different from the winter. always presenting the winter significantly differing from the summer. We identifyied low p-values for the summer differing from spring, but not between summer and autumn. Reported impacts during autumn present no significant differences compared to the other seasons.

Although the seasonality of EDII$_{ALPS}$ and the EDII$_{EU}$ is rather similar for the domains, some categories show differences. Impacts related to *Agriculture and livestock farming* occurred in all seasons in the EDII$_{ALPS}$, wherefore it is the dominating category throughout the year excluding winter. *Agriculture and livestock farming* in In the entire EDII$_{EU}$ this category on the other hand dominates dominates only during summer and *Public water supply* is the most dominant category at other times of the year (Fig. 4a,b). Regarding *Agriculture and livestock farming*, we observed most of these impacts in the summer in all subdomains as wellcovered by the EDII$_{ALPS}$, with a strong increase before summer, followed by a strong and a decrease after the summer months. The pre-Alpine and Southern region show a clear increase of impacts in March and April (Fig.4c,f), and the high-altitude region has substantially higher counts in September and October (Fig. 4d). In the EDII$_{ALPS}$Alpine Space, the spring and summer impacts in this category related most to the subtype 'Reduced productivity of [...] crop cultivation' (1.1, 1.2), whereas the impacts in autumn related most to 'Reduced availability of irrigation water' (1.4). The EDII$_{ALPS}$ reported impacts in *Public water supply* were are less frequent compared to the ones by the EDII$_{EU}$, and especially in the first months of the year till May. The high-altitude region shows the most different pattern compared to the other domains by the EDII$_{ALPS}$Europe (Fig. 4ab, c,d, e,f). In these domains, Tthe monthly sums of this category do not increase in spring, but start to accumulate from May to August with high fractions in the high-altitude region. There, impacts on *Public water supply*, and arewere less but still frequently reported in autumn. Especially in November and December, the reported impacts showed the same fractions as those related to *Agriculture and livestock farming*. In the EDII$_{ALPS}$ the most frequent subtype 'Bans on domestic and public water use' (7.3) dominated this category, whereaswheres in the EDII$_{EU}$, the subtypes 'Local [...] and region-wide water supply shortage/ problems' (7.1, 7.2) arewere as well prominent.

The EDII$_{ALPS}$' category *Freshwater ecosystems* reportsed most impacts in summer and autumn and almost none in spring and winter, with reports mostly located in the Northern region respectively pre-Alpine region (Fig. 4c,e). The EDII$_{EU}$ presented presents as well most counted reports in the summer months, but the fractions of this category spread more equally across the seasons. Further, we identified identify most impacts related to *Forestry* to occur in summer for both, in the EDII$_{ALPS}$ Alpine Space and in the EDII$_{EU}$Europe. Within the domainssub-regions of the EDII$_{ALPS}$ Alpine Space, we observed the seasonal fraction of *Forestry* impacts in relative terms to be varying in relative terms. We depicted the lowest relative fractions in autumn, which is due to higher counts in spring and summer especially in the Northern region (Fig. 4e) and higher counts in winter in the high-altitude region (Fig. 4d). In the EDII$_{ALPS}$Alpine Space and in the EDII$_{EU}$Europe, we found find most frequent reports in *Waterborne transportation* from high summer to early September and with highest seasonal fraction in autumn (Fig 4a,b). Impacts related to *TourismTourims and* *recreation* differ~~ed~~ in their seasonal ~~distribution~~ fractions between the domains. In the EDII$_{ALPS}$~~Alpine Space~~, these impacts ~~were~~ are mostly winter impacts with a majority located in the high-altitude and Southern region (Fig. 4a,d,f). Additionally, the high-altitude region ~~showed~~ shows higher fractions in spring for this category. Though the pre-Alpine and Northern region report~~ed~~ most impacts in summer, similar to the EDII$_{EU}$~~Europe~~, these records are few compared to the more frequent categories, such as *Agriculture and livestock farming* and *Public water supply*. We also ~~found~~ find a few impacts on *Air quality* in the EDII$_{ALPS}$ and the EDII$_{EU}$. In the EDII$_{ALPS}$ ~~Alpine Space~~, this category together with *Tourism~~Tourims~~ and recreation* ~~were~~ are the only ones reported most in autumn (*Air quality*) and winter (*Tourism~~Tourims~~ and recreation*).

Table 2. Results of~~by~~ the *Pairwise Wilcoxon Rank Sum Test comparing the central tendencies between the different seasons in all domains*. Only~~We limited the shown results to those~~ combinations differing by~~with~~ a p-value <= 0.15 are shown. ~~We marked regions with no pairs with '-' and pairs with significant differences with '*' (p <= 0.05).~~

Regions	Seasons~~[1]~~	P-value~~[2]~~[1]
Europe	Summer:Winter	0.030~~43~~*
Alpine Space	Summer:Spring	0.117
	Summer:Winter	0.05~~8~~3
Pre-Alpine region	Summer:Spring	0.109
	Summer:Winter	0.019~~28~~*
High-altitude region	-	-
Northern region	Summer:Spring	0.067
	Summer:Winter	0.017~~20~~*
Southern region	-	-

~~1 seasonal pairs whose central tendencies differ with a p-value ≤ 0.15.~~

~~2 marked with '*' for the significant p-value ≤ 0.05.~~

[1] `*´significant at p-value ≤ 0.05. '-' no combination differing with p-value ≤ 0.15.

3.4 Impacts related to drought types

We re-grouped 42 out of 96 subtypes by their related drought type D_{SM} and D_H (Fig. 5a). Twelve subtypes ~~were~~ are classified as D_{SM} impacts with most of them from the categories *Forestry* and *Agriculture and livestock farming*. Further, we classif~~yied~~ 32 subtypes as D_H impacts with a majority from the categories *Water quality*, *Public water supply*, and *Freshwater ecosystems*. Two subtypes ~~were~~ are classified into both, the D_{SM} group and the D_H group: 'Lack of feed/water for livestock' (1.7) and 'Lack of feed/water for wildlife' (10.8), as low soil moisture as well as low discharge and/or groundwater storage are appropriate drivers. For 54 subtypes neither D_{SM} nor D_H ~~was~~is considered as a clear trigger. They ~~were~~ are classified into a group of indirect impacts that include impacts less tangible to specific drought conditions and strongly dependent on market situations, management and governance aspects. We

~~found~~ find most of these ambiguous subtypes in the categories *Energy and industry*, *Human health and public safety*, *Air quality*, *Conflicts*, *Freshwater ecosystems* and the subtype 'Increased costs/economic losses' in several categories (all assignments are presented in Table S1).

With this classification scheme, the fraction of D_{SM} and D_H impacts differ clearly per domain (Fig 5). In the EDII$_{ALPS}$~~Alpine Space~~ 38~~6~~ % of all impacts ~~were~~ are assigned to D_{SM} and 40~~3~~ % to D_H. In the EDII$_{EU}$~~Europe~~, D_{SM} impacts ~~were~~ are less (23~~2~~ %) and D_H impacts (55~~6~~ %) more frequent (Fig. 5a,b). In the pre-Alpine region, 40~~38~~ % of the impacts ~~were~~ are assigned to D_{SM} and 39~~42~~ % to D_H. In the high- altitude region, we assign~~ed~~ less impacts to D_{SM} (25~~3~~ %) and more to D_H (52~~6~~ %) (Fig. 5c,d). The Northern and Southern region differ~~region compared differed~~ less with 36~~5~~ % and 41~~37~~ % assigned to D_{SM} and 39~~40~~ % and 42~~49~~ % assigned to D_H (Fig. 5e,f). The Southern region shows the greatest fraction of combined D_{SM} and D_H impacts (83~~6~~ %) among all domains.

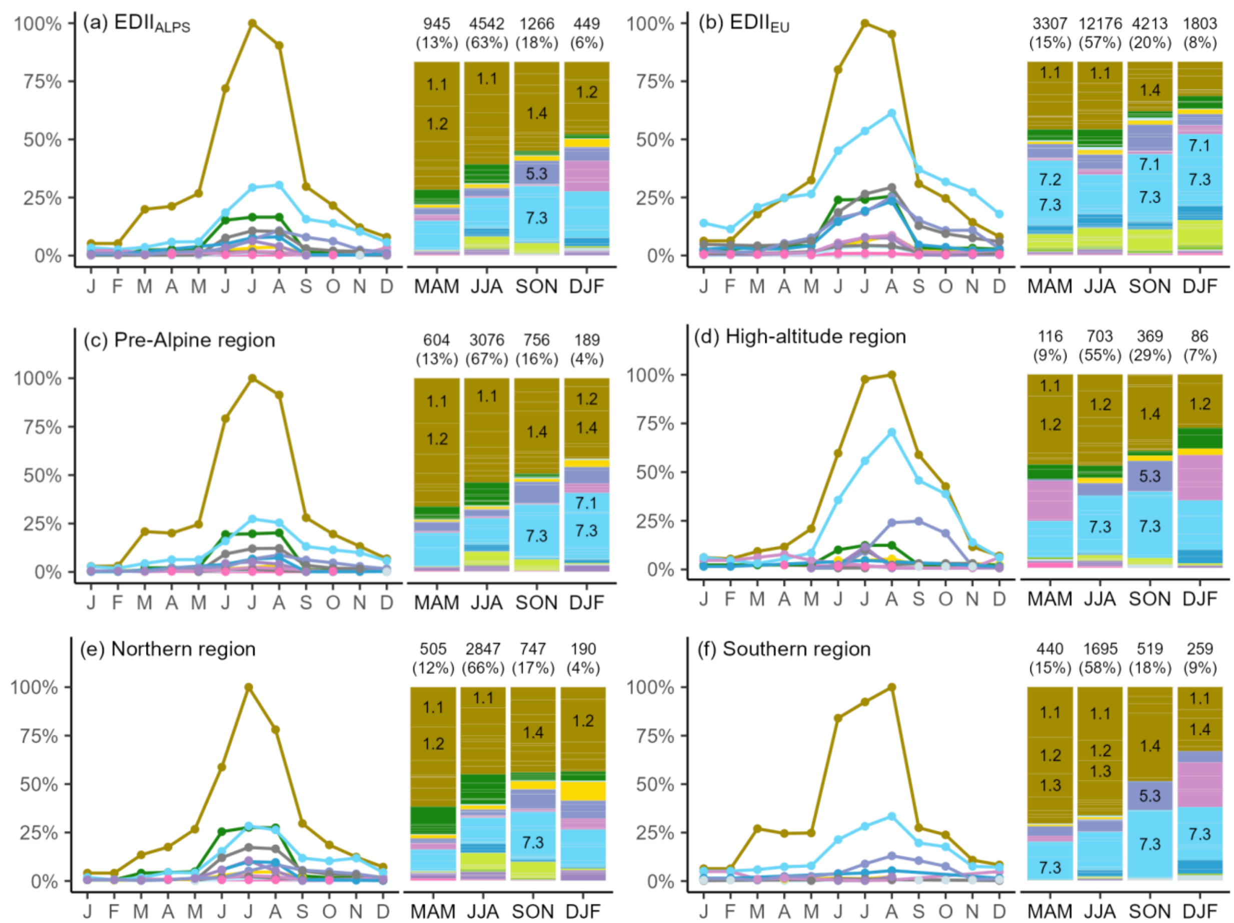

Figure 4. D~~Annual d~~istribution of reported impact categories ~~aggregated~~ per month (line diagrams) and season (bar plots) for the (a) EDII$_{ALPS}$~~Alpine Space~~, (b) EDII$_{EU}$~~Europe~~, (c) pre-Alpine region, (d) high-altitude region, (e) Northern region, (f) Southern region. Monthly percentages~~values~~ relate to the sum of all impacts per month and category with 100 % corresponding to the month with~~are related to frequency of the month with~~ most impacts. Total counts of each season are given on top of the bars, the fraction ~~proportion~~ in brackets relates to the amount of impacts assigned to the season. Subtypes with a fraction ~~proportion~~ ≥ 10 % per season are labeled. Colours see Fig. 2.~~Colours correspond to the legend of Fig. 2.~~

In the D_H impact group, the most frequent subtypes are 'Bans on domestic water use' (7.3), 'Local water supply shortage/problems' (7.1), 'Reduced availability of irrigation water' (1.4), 'Regional shortage of feed/water for livestock' (1.7), and 'Increased mortality of aquatic species' (9.1). We ~~found~~ find the largest proportional differences between the pre-Alpine and high- altitude region among the subtypes 'Reduced availability of irrigation water' (1.4), and 'Bans on domestic and public water use' (7.3). Accordingly, we observe~~d~~ a shift among these subtypes between the Northern and Southern region, but additionally for the subtype 'Increased mortality of aquatic species' (9.1). Both differences confirm the previous results. In the D_{SM} impact group, the most frequent reports are in the category *Agriculture and livestock farming* and about the subtypes 'Reduced productivity of annual crop cultivation' (1.1), 'Reduced productivity of permanent crop cultivation '(1.2), 'Agricultural yield losses ≥ 30 %' (1.3) and 'Regional shortage of feed/water for livestock' (1.7). The different fractions for these subtypes depend~~ed~~ on the domain. The Southern region reports~~ed~~ the largest~~ relative~~ fraction of impacts about 'Reduced productivity of annual crop cultivation' (1.1), 'Reduced productivity of permanent crop cultivation' (1.2), 'Agricultural yield losses ≥ 30' (1.3). Within the D_{SM} impacts, *Forestry* impacts ~~were~~ are substantially less frequent and non-existent in the Southern region.

The annual regime curves of the D_{SM} and D_H impacts are based on monthly reported impact sums. For all domains most D_{SM} and D_H impacts occurr~~ed~~ in summer and early autumn as already shown in the previous results. In case of D_{SM} impacts, the high occurrence peaks are~~were~~ driven by 'Reduced productivity of annual crop cultivation' (1.1). Regarding the D_H impacts, the high peaks correspond to 'Local water supply shortage / problems' (7.1) in the Northern region and to 'Bans on domestic and public water use' (7.3) in all other domains.

According to the total counts of the grouped impacts by drought types, the $EDII_{ALPS}$~~Alpine Space~~ has a higher D_{SM} impact peak occurring earlier in the year (June-July) than the D_H impact peak (July-August) (Fig. 5a). In addition, the increase and decrease of the D_H curve happens later in the year than that of the D_{SM} curve. Thus, between March and July D_{SM} impacts show higher fractions, while between September and December D_H impacts show higher fractions. The $EDII_{EU}$ contrasts these results (Fig. 5b), as the records across Europe depicted the highest~~r~~ peak of D_H impacts in the same summer months compared to~~as~~ the D_{SM} impact peak. Within the $EDII_{ALPS}$ the delayed D_H peak and the higher fractions of D_H impacts between September and December is confirmed by all paired~~sub~~ domains (Fig. 5c,d,e,f). The most different pattern ~~was~~ is found for the high-altitude region with the latest onset of the D_H impact curve and a delayed peak between August and September (Fig. 5d). Furthermore, this ~~was~~ is the only domain within the Alpine Space with a higher D_H impact peak, and subsequently, the highest fractions between July and December.

4 Discussion

4.1 Drought impacts across the European Alpine region

Although the Alpine Convention has started to raise the topic, drought impacts in different regions of the Alpine and pre-Alpine area have not yet been formally compared. Assembling the $EDII_{ALPS}$, an inventory of drought impact reports, ~~now~~ enable~~d~~s a first overview and some regional comparisons. Any collection of drought impact data is a challenging task due to~~because of~~ the lack of ~~difficulties related to~~ a clear definition of ~~a~~ drought impact's onset and end~~termination for multifaceted causes~~ (Bachmair et al., 2015). The report collection enables this link, as we only

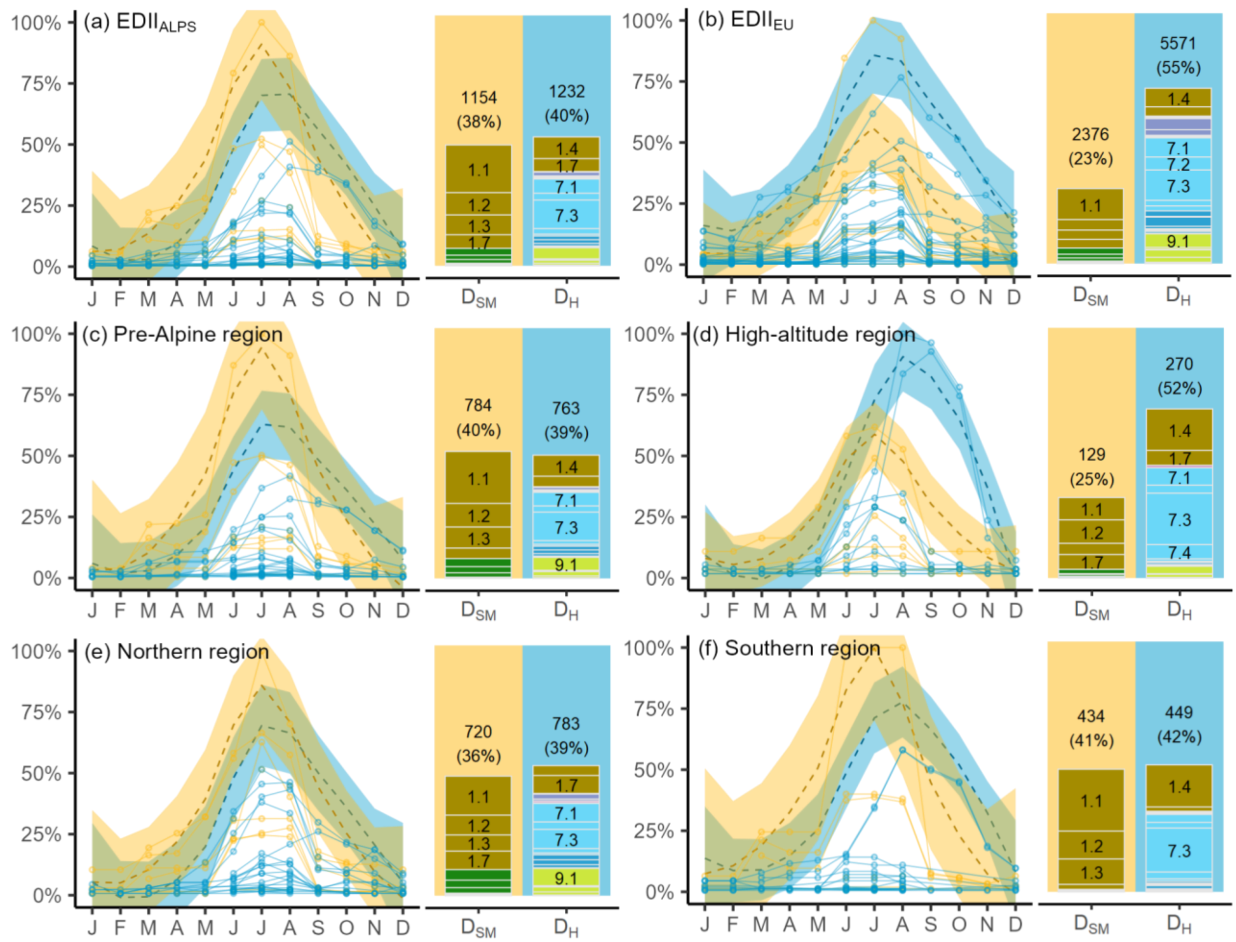

Figure 5. Impact subtypes assigned to D_{SM} (yellow) or D_H ~~types~~ (blue)~~. D_{SM} and D_H impacts aggregated~~ per month (line diagram) and drought type (bar plot) for the (a)$EDII_{ALPS}$ ~~Alpine Space~~, (b) $EDII_{EU}$ ~~Europe~~, (c) pre-Alpine region, (d) high-altitude region, (e) Northern region, (f) Southern region. Seasonal regimes for D_{SM} (yellow lines) and D_H impacts (blue lines) are loess curves with standard errors (dotted line with coloured shape).~~-~~ Monthly percentages~~values~~ (solid lines) relate to the sum of all impacts per month and subtype with 100 % corresponding to the month with most impacts.~~Monthly values are related to frequency of the month with most impacts.~~ Total counts of D_{SM} and D_H impacts are given on top of the bars, the fraction ~~proportion~~ in brackets relates to the amount of impacts assigned to the season. Subtypes with a fraction ~~proportion~~ ≥ 5 % are labeled. Colours see Fig. 2.~~The colours of the subtypes correspond to the legend of Fig. 2.~~

compiled reports clearly stating drought to be the cause of the described impact. ~~The chosen data sources proved to be suitable, as impacts were clearly linked to the droughts occurrence as the cause for the collected impact report.~~ Some impacts can be measured and are therefore easier to collect and hence more consistent through time and space (e.g., the agriculture yield losses), but most of them are hard to quantify (Logar and van den Bergh, 2013). For most of the impacts no continuous data is available, for which the text-reports proved to be a suitable surrogate and are worthwhile to collect (Bachmair et al., 2016; Hayes et al., 2012). Nonetheless, not all impacts are reported or only reported locally, in which case the compiled information in EDII$_{ALPS}$ V1.0 may still have gaps. 70 % of all reports stem from~~located in~~ the Northern region~~ are mostly oriented toon the maritime climate~~. We have been expecting the Southern region characterised by Meditarranean climate to be at least equally impacted but~~and~~ assume our impact data might be regionally more complete in the Northern region. On the other hand Mediterranean regions may~~could~~ be better prepared for drought or ~~depict infrequent reporting on drought impacts,~~ as dry and hot conditions are more common are less concerned with reporting them. In addition, we might have missed drought impacts that are not reported to be associated with drought due to the typical perception that mountain regions are water-rich. Especially winter drought might be still underestimated, as impacts caused by low snow accumulation can occur delayed and therefore might not be associated with~~ linked to~~ climatic~~drought~~ conditions months ag~~o~~. Despite these barriers, the amount of impact data we collected for the EDII$_{ALPS}$ ~~within the Alpine Space~~ (n: 3243) demonstrates that drought impacts have been present in the European Alpine region. Despite the humid mountain climate, 30 % of all impact data across Europe is located in our study region. Subsequently, this study confirms the relevance to understand the role of drought as well in the European Alpine region and not only in low-altitude areas.

Most of the EDII$_{ALPS}$' recent data stem from newspaper articles, web pages, governmental reports and scientific articles and specialty databases. We analysed the impact data differences between the ~~Alpine Space~~ EDII$_{ALPS}$ and the ~~Europe~~ EDII$_{EU}$, as well as between ~~for~~ the paired domains (pre-Alpine and high-Alpine, Northern and Southern region) and between~~for~~ political units (countries, ~~and~~ NUTS 2 ~~and 3~~ regions) within the Alpine Space.

Similar to the EDII$_{EU}$ ~~all of Europe~~, most reported impacts in the EDII$_{ALPS}$ ~~Alpine Space~~ fell into the category *Agriculture and livestock farming*, specifically to the subtype 'Reduced productivity of annual crop cultivation' (1.1). In contrast to the Northern region, the Southern region is known for less precipitation and higher air temperatures due to the Mediterranean climate. Even though the region adapted partly to the climatic conditions with permanent irrigation systems (Yves et al., 2020), we found substantially more impacts related to *Agriculture and livestock farming*. Haslinger and Blöschl (2017) showed that drought frequencies were higher in the Southern region and hence also the exposure for impacts. Relatively, even more impacts in *Agriculture and livestock farming* were reported by the EDII$_{ALPS}$~~for the Alpine Space~~ than by the EDII$_{EU}$ ~~for entire Europe~~. It should be kept in mind that the EDII$_{ALPS}$ covers the 'Alpine Space', and therefore includes not only the mountains but large foothill and foreland areas as well (Fig. 1). Besides urban areas such as Vienna, Milan or Zurich, the Alpine Space is known for its agricultural crop production in lower elevation areas and for mountain pastures for beef and dairy production typical in higher elevated areas (Jäger et al., 2020). Subsequently, in this region *Agriculture and livestock farming* is among the most relevant economic sectors (Flury et al., 2013). This dependence potentially affects the vulnerability and hence has ~~drove~~ driven the number of reported impacts we compiled compared to the EDII$_{EU}$~~whole of Europe~~ with less economic dependency on the agricultural sector.

The second most frequent impact category in the EDII$_{ALPS}$~~Alpine Space~~ relate~~s~~d to *Public water supply*. ~~Relatively however, it is less relevant C~~c~~C~~ompared to the EDI$_{IEU}$~~Europe~~ this impact category ~~is~~was less relevant, hence confirming the typical association that the European Alpine region is a water-rich Water Tower (Viviroli et al., 2007).

Nonetheless, the amount of reports for the subtype 'Bans on domestic and public water use' (7.3) emphasizes the need to develop management strategies. Specifically, for periods of particular high water demand compared to its actual availability, e.g. periods with high demand for supplementary irrigation or for high touristic uses. The fraction of impacts related to *Public water supply* was highest in the high-altitude region, but it was not high in absolute number. To fully explain this result, further studies need to investigate whether ~~Whether~~ upstream headwater areas have to deal with impacted water supply, or less access to stored water compared ~~to allocated water~~ to lower (downstream) areas with allocated water. ~~will have to be studied further to fully explain this result.~~

Impacts classified into the category *Freshwater ecosystems* were less reported and it may be concluded that they might be less relevant in the EDII$_{ALPS}$~~Alpine Space~~ compared to the EDII$_{EU}$~~Europe~~. However, in the Northern region the categories' fraction was higher, mainly driven by reports from Switzerland and Germany exceeding the fraction of the EDII$_{EU}$~~European average~~. Most of these reports were located along the river Rhine and associated with high water temperatures and less oxygen saturation in the year 2003. Drought impacts on *Forestry* were more relevant in the EDII$_{ALPS}$. This category ranked 3rd compared to 6th in the EDII$_{EU}$. Most of these impacts were located in Germany and Switzerland. The majority of German reports originated from governmental reports by national and regional agencies, such as the ~~ressort of~~ forest institutes ~~science~~ by the federal state Baden-Wurttemberg or Bavaria that regularly publish articles about the forest conditions in Southern Germany. We found similar reports in Switzerland, but not in the other Alpine countries. Thus, EDII$_{ALPS}$ likely still misses *Forestry* impacts in other regions. The drought impact categories *Waterborne transportation* and *Water quality* appear to be less relevant in the EDII$_{ALPS}$ ~~Alpine Space~~ compared to the EDII$_{EU}$~~Europe~~. Reasons may include *Waterborne transportation* to take place in the lowlands and *Water quality* benefitting from less pollution and environmental degradation. Other impact categories did not show substantial differences. Even though hydropower has a greater~~larger~~ importance in mountainous regions, the number of reported impacts in Energy and industry in EDII$_{ALPS}$ d~~oes~~id not differ compared to EDII$_{EU}$. One reason among others might be related to the ~~dependency of most~~ hydropower generated from~~on~~ reservoir storage, which makes operations~~it~~ more resilient towards drought events.

The differences between the impact data of the Alpine countries are influenced by the sources we investigated. Comparable to EDII, the Unwetterchronik, Drought-CH as well as the text-report collection for Germany and Italy offer varied information about the droughts' impacts. In contrast to these more broad databases, the bulletins from DMCSEE and the Slovenian text-reports are more focused on impacts related to agriculture and the French "Propluvia" informs on water restrictions in drought periods. The resulting report based impact data collection EDII$_{ALPS}$ is therefore influenced by national priorities and different collection efforts effects, a limitation Stahl et al. (2016) as well discussed. Our statistical tests confirmed this spatial heterogeneity. Nonetheless, we should consider the national focus as valued information, because this likely depicts the current major challenges of drought management on the national scale, but further efforts might focus on complementing them. Despite these differences, EDII$_{ALPS}$ depicts plausible patterns in altitudinal and climatic subregions in the Alpine Space.

4.2 Drought events and temporal impact trends

The reported impacts compiled in $EDII_{ALPS}$ ~~Reported impacts~~ identified four specific drought years in the Alpine Space: 1976, 2003, 2015, and 2018. Studies focusing on drought events across the European mountain region are scarce, wherefore it is difficult to relate the impact based drought years to climatologically identified drought events in the Alpine Space. Haslinger et al. (2017) presented no clear drought trend from 1801 to 2010, but ranked the 2003 drought as the second most severe event, likely resulting in our substantial increase of reported impacts. Brunner et al. (2019) compared the drought events 2003, 2015 and 2018 due to the severe ecological, economic and social impacts in Switzerland confirming our identified drought years with the $EDII_{ALPS}$. On the European scale several studies call the years 1976, 2003, 2015 and 2018 'drought events' identified by various selection methods, most based on drought indices respectively the detection of anomalies (Parry et al., 2012; Spinoni et al., 2015;~~,~~ Laaha et al., 2017; Hoy et al., 2020;~~,~~ Hari et al. 2020). This leads to the assumption that the $EDII_{ALPS}$ complements these studies with evidence of impacts ~~as a whole database~~ (Fig. 3a) reflecting~~s~~ the hazards potential of ~~for~~ severe drought events. ~~, L but might miss l~~Less severe droughts or droughts with less public attention might not be sufficiently represented.

Further, the $EDII_{ALPS}$ suggests a diversification of impacts over time ~~suggest a diversification over the main drought years from 1976, 2003, 2015 to 2018~~, confirming observations in earlier studies with the $EDII_{EU}$ (Stahl et al., 2016). The impacts of the drought in 1976 differed substantially from later events~~the others~~, as more than 80 % of all impacts related to *Agriculture and livestock farming*, followed by *Forestry*. Parry et al. (2012) explained the unprecedented severity of the drought event 1975-76 by the consecutive occurrence of winter and summer drought likely explaining the high number of impacts archieved in $EDII_{ALPS}$. The dry starting conditions in spring and early summer not only affected *Agriculture and livestock farming*. In addition, possibly *Forestry* was as well affected already during winter, but showed the impacts delayed the next summer. An effect that the data also suggest ~~we relate as well~~ for~~to~~ the droughts in 2015 and 2018. In terms of higher impact diversification the years 2003, 2015 and 2018 depicted a more comparable picture than 1976. ~~The other major drought events of the years 2003, 2015 and 2018 depicted a more comparable picture A remarkable difference of the impacts in~~ 2003 differed the most from 2015 and 2018 with ~~to the more recent events were~~ the high fractions of the category *Freshwater ecosystems* and *Water quality*. According to the previous section, these impacts correspond to the river Rhine in Northern Switzerland and Southwest Germany. The characteristics of the 2003 drought ~~2003~~ have been a combination of ~~a~~ heatwaves especially in central Europe combined with very dry summer conditions (Schär and Jendritzky, 2004) leading to high water temperatures and low oxygen levels firstly reported as impacts in the category *Water quality*. Finally, these impacts have led to the great fish dieback, reflected by the subtype 'Increased mortality of aquatic species' (9.1) of the category *Freshwater ecosystems*. Blauhut et al. (2015) associated the~~is~~ report's increase with the new EU Water Framework Directive, which raised the topic's attention. ~~In 2003, the high water temperatures and low oxygen levels were firstly reported as impacts in the category *Water quality*, but finally led to the great fish dieback, reflected by the subtype 'Increased mortality of aquatic species' (9.1) of the category *Freshwater ecosystems*.~~ The years 2015 and 2018 showed substantially increasing reports related to *Forestry*. ~~These impacts might be the response to the sequence of persistent dry and warm periods in-between, which accumulate in dry soils and subsequently soil-moisture drought~~. Lahaa et al.

(2017) compared the drought 2015 to 2003 and presented 2015 with drier starting conditions along the Northern Alps and the notably longer duration in Southern Germany. Hari et al. (2020) characterized the drought 2018 persisting into 2019, unlike 2003, where ecosystem carbon and energy fluxes recovered early after the summer. Thus both droughts in 2015 and 2018 were characterized by a longer duration that accumulates in dry soils and subsequently D_{SM}. The increased fractions of *Forestry* impacts in 2015 and 2008 compared to 2003 ~~increase of *Forestry* impacts~~ likely reflect these persistent characteristics~~characterictics~~ of D_{SM}~~soil-moisture drought~~ accumulating longer ~~than one year~~ and thus depict delayed impacts. Trotsiuk et al. (2020) showed substantially stronger negative trends by the species Fagus sylvatica and Picea abies of forest productivity in Switzerland for the year 2018 compared to 2003. Alt~~T~~hough~~,~~ they did not analyze the year 2015, the results for 2018 likely correspond to accumulated effects. Ogle et al. (2000) predicted higher tree mortality following severe droughts and McDowell et al. (2010) suggested the drought-induced lower, but more continuous mortality of tree species occurring delayed due to several interdependent physiological mechanisms. We observed a similar but less prominent pattern for the category *Waterborne transportation* between the years 2003 and 2018 that might correspond to a longer lasting D_H ~~hydrological drought~~, with less discharge and/or groundwater storage over the years.

Over the whole time period, the number of collected drought impacts increased, especially after 2000 and 2010. This trend is influenced by (1) general reporting behaviour changes with digitization and online media availability (regardless of the sources, such as scientific or newspaper articles or governmental reports), (2) accessibility to drought reports in the recent past being easier than to historic information (3) awareness of the drought hazard having increased along with climate change. For the most recent droughts, reports are yet to be published. Thus, the decreasing number of reports especially for the last ~~five~~ two years is likely a delayed effect of publishing and collecting such text-based impact information. Nevertheless, we presented significantly different values for the years 2003, 2015 and 2018, which correspond well to the major drought events after 2000. Additionally, 1976 depict~~s~~ed substantially more impact data, in a time where digitalization and the accessibility to online articles had been very different compared to the last 20 years. Thus, we expect our time trend to be biased. ~~and with 70 % of all reports located in the Northern region mostly oriented on the maritime climate. Droughts in the Southern region, might have been too local to affect the general development.~~ However, the EDII$_{ALPS}$ as a whole still depicts~~ed~~ the major events and the tendency of increased impacts.

4.3 Seasonal patterns and delayed impacts

Summer and early autumn ~~are~~ were the seasons with most drought impacts in all domains regardless of impact category or drought type. This confirms the expectation that drought impacts occur most frequently ~~especially~~ in summer. Additionally stressed by evapotranspira-tion, this season has the highest water demands, and hence, higher potential water shortages occur despite a mostly balanced annual precipitation in the Northern and Western parts of the Alpine Space (Kruse et al., 2010). In early autumn natural soil and catchment water storages are depleted. This low flow season, known from low elevated regions (Laaha and Blöschl, 2006), also leads to drought impact occurrences. The statistical tests provide~~s~~d proof that~~for~~ the summer season ~~differs~~ differed significantly from winter, but not from autumn.

Summer and often early autumn impact occurrences were dominated by~~dominance most clearly shown for the impact categories~~ the categories *Agriculture and livestock farming* and *Public water supply*. We indeed observed higher fractions of autumn impacts in the high-altitude region mostly related to *Public water supply*, followed by 'Reduced availability of irrigation water' (1.4). The relevance supports the expec-tation that water supply depends not only on direct precipitation, but also on natural water storages feeding springs used for drinking water. Reservoirs are likely managed differently across the Alpine Space, depending on the reservoir location and purpose. Hence, clarifying upstream-downstream dependencies would be a prerequisite to understand in more detail, why and where impacts have happened. Regarding the Alpine Space, autumn ~~does~~ did not differ significantly from summer, thus highlight-ing the importance of this season for the European Alpine region.

Although we found ~~presented~~ least winter impacts, this season should not be neglected. Several studies show~~ed~~ winter as an essential part of the droughts development, and suggest~~ed~~ the delayed effects by summer and autumn accumulating in winter and winter as the early driver for upcoming impacts in the following seasons (van Loon et al., 2010; Livneh and Badger, 2020). Our compiled winter impacts differed slightly by their composition. The fraction of impacts related to *Agriculture and livestock farming* decreased (especially in the high-altitude and Southern region) with the last crop harvests in autumn. The impacts in the categories *Public water supply* and *Waterborne transportation* ~~are~~ were also less in winter but with comparable ~~relative portions~~fractoins as in autumn. In contrast, impacts on *Tourism~~Tourims~~ and recreation* peak~~ed~~ed in winter, driven by the high-altitude region (all impacts from the southern region in this category were as well located in the high-altitude region). In the EDII$_{\text{ALPS}}$ most impacts in this category reported limited snow availability and snow production, both threatening ski tourism. Several studies raise the topic's attention, as ~~the~~ drought harming tourism ~~problem is real and~~ should not be ignored in management of snow tourism in mountain regions (Abegg et al., 2007; Gilaberte-Búrdalo et al., 2014; Spandre et al., 2019).

In almost all domains, more than 10 % of all impacts occurred in spring~~.~~ and the highest fraction was~~of them~~were located in the Southern region (14 %). ~~In the Alpine Space, the Southern region reported the most impacts in spring, which~~ This can~~ould~~ be related to the Mediterranean climate that is in general warmer and drier also in the early stage of the year causing an earlier start of ~~and hence~~ the vegetation season~~starts earlier~~. A corresponding example published in April, 2020 by an Italian newspaper is ~~summarized~~ summarised as follows: "In the Brescian area, emergency irrigation was carried out on wheat, barley and fodder, but also on freshly sown corn. [...] In some cases the seedlings begin to dry out. Maize is also suffering: sowing took place between the end of March and the first days of April, but the lack of rainfall is compromising growth [...]. In some cases, farmers preferred to postpone sowing. Wherever possible, emergency irrigation is used [...]". The constitution of the EDII$_{\text{ALPS}}$' spring impacts differed from that of the EDII$_{\text{EU}}$. We found substantially less impacts related to *Public water supply*. In mountain regions, the precipitation in winter does not evaporate as quickly as in lower elevated regions and soil moisture may replenish. In higher elevations, precipitation~~it~~ is first stored as snow and will not replenish the water storages~~, (both soils and artificial reservoirs),~~ before all snow is melted around July (both soils and artificial reservoirs) - or even later if glacier melt is used for filling water storages. Both processes likely mitigate water shortages in spring in mountain areas, leading to less DH~~hydrological drought~~ impacts related to low discharge and groundwater storage. Furthermore, we found a higher fraction of *Forestry* impacts occurring in the Northern region. Delayed summer and autumn effects ~~could~~ can persist over winter, especially in winters with temperatures cold enough to hinder precipitation to function as soil water, as it is stored in snow (van Loon et al., 2010). This could can lead to dry soil and vegetation more vulnerable to drought. Additionally, most plants reduce their water intake during the cold season, to be less prone to frosts (Theocharis et al., 2012). Thus, cold winters high up do not prevent drought impacts in spring., what we likely observed with the *Forestry* impacts in the Northern region. The high fraction of impacts related to *TourismTourims and recreation* in the high-altitude region is mostly due to ski tourism lasting into spring.

The $EDII_{ALPS}$ reveals several delayed effects between impact categories. A delayed start and termination of DHhydrological drought impacts in all domains confirmed confirms the expectation that drought types occur in a particular order, which is not as clear in the $EDII_{EU}$. Further, all domains reported more higher total counts of $D_H$hydrological drought impacts compared to D_{SM}soil moisture drought impacts in all domains underlyingines the assumption thatassumptioneffect that drought impacts frequencies increase accumulated over time. Both effects were shown to be strongest in the high-altitude region. In the high-altitude region, snow accumulation in winter and in general lower air temperatures lead to better water availability in spring and early summer and subsequently, as shown by our results, less impacts (smallest fractions of impacts in spring and summer). Further, this typical mountain hydrology likely delays the $D_H$hydrological drought impacts, as water released by snowmelt leads to longer water availability of natural storages typical for upstream areas. This effect could be found in all domains of the $EDII_{ALPS}$, but not in the $EDII_{EU}$. However, the high-altitude region experienced relatively the most $D_H$hydrological drought impacts later in the year, showing the regions dependency on water and the need for management strategies also in upstream areas.

The impact specific seasonalities in combination with spatial differences may need different seasonal indices in an impact-targeted drought monitoring and early-warning system across the Alpine region. Stagge et al. (2015) and Bachmair et al. (2016) presented different methods to model and predict impact occurrences with report-based datasets that could be applied to $EDII_{ALPS}$. In addition, to inform risk assessments at smaller scales a more complete spatial coverage of drought impact data collection is essential.

5 Conclusions

The presented $EDII_{ALPS}$ constitutes the first comparative view of drought impacts across the European Alpine region. . Most of the $EDII_{ALPS}$' recent data stem from newspaper articles, web pages, governmental reports and scientific articles and specialty databases with a majority reporting drought impacts on *Agriculture and livestock farming* and *Public water supply*. Between the sources covering the Alpine countries the focus varied: Comparable to EDII, the Unwetterchronik, Drought-CH as well as the text-report collection for Germany and Italy offered varied information about the droughts impacts. In contrast to these more broad databases, the bulletins from DMCSEE and the Slovenian text-reports were more focussed on impacts related to agriculture and the French "Propluvia" informed on water restrictions in drought periods. The resulting report based impact data collection $EDII_{ALPS}$ is therefore influencedshaped by national priorities and different collection effortssocietal effects. Our statistical tests confirmed this spatial heterogeneity. Nonetheless, we should consider the national focus as valued information, because this likely depicts the current major challenges on the national scale in drought management, but further efforts might focus on complementing them. Despite this differences, EDII$_{ALPS}$ depicts plausible patterns in altitudinal and climatic subregions in the Alpine Space and The mountain specific database covering different countries may serve as an example how international collaboration can customize customise existing databases such as the EDII with a moderate effort to make them useful in regions that have previously not really been a focus. Mountain regions are usually not related to drought impacts due , according to their water-rich character. Nonetheless, Ouour study presented the European Alpine region vulnerable to the hazard of drought, despite the water-rich character. We compiledEDII$_{ALPS}$ archives a great amount of impacts mostly related to agriculture and livestock farming followed by public water supply. These affected sectors are firmly established in the region, wherefore adaption and management strategies are essential for the future climate regimes. Apart from the most relevant sectors, we found present a surprising diversity of impacts covering a wide range of environmental, economic and societal effects that confirm the multifaceted character of drought in the EDII$_{ALPS}$Alpine Space. This growing diversity over time is likely due to the increasing complexity of the socio-economy across the European Alpine regionin the Alpine Space with various sectors exposed and/or vulnerable to drought. In addition, the number of impacts increasesd substantially over time.

Key characteristics of drought impacts in the region are that impacts mostly occur in summer and early autumn regardless of region, climatic condition or altitude. Typical to EDII$_{ALPS}$ are also some winter impacts related to ski tourism while spring impacts occur mostly in the southern region. The regions' specific snow accumulation in winter likely mitigates water shortages through snowmelt contributions in spring and early summer. Further, we couldthis study proves the possibility to link impacts to hydrological drought and soil-moisture drought in order to analyse drought specifics in different hydrological and climatic conditions. For the mountainous regions, we could demonstrate the delay between impacts classified as related to soil-moisture drought and those classified as related to hydrological drought. For the mountainous regions, we could demonstrate the delayed effect between impacts caused by soil-moisture drought and hydrological drought, especially for the higher elevated region. All these seasonal effects of water redistribution and demand are essential to understand drought as a the hazard across potential in different climatic and altitudinal zones. Therefore, for which our study presents a good starting point from the impact perspective. Despite some biases in the current database, the amount of impacts we compiled in the EDII$_{ALPS}$ should raise awareness. Future climate predictions with increased drought severity, less snow and shift in precipitation patterns, suggest the European Alpine region will be further impacted by vulnerable to drought impacts. For drought risk assessments and management strategies EDII$_{ALPS}$ will have to be analysed and adapted further by more complete spatial coverage on the local scale and by modelling impact occurrence to predict the future potential of drought impacts. This has to be taken into account for drought risk and management assessments.

Data availability. The EDII$_{ALPS}$ V1.0 (last update 8th of January, 2021) is available under 10.6094/UNIFR/218623 We plan to publish the EDII$_{ALPS}$ data with a DOI.

Author contributions. Ruth Stephan, Mathilde Erfurt and Kerstin Stahl, designed the research. All co-authors provided data. Ruth Stephan moderated all EDII$_{ALPS}$ entries, carried out the analysis and created the graphs, maps and tables in the manuscript. Ruth Stephan prepared the manuscript with contributions from Mathilde Erfurt and reviews from all co-authors.

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